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THE NASA ADVANCED PROPULSION CONCEPTS PROGRAM AT THE JET PROPULSION LABORATORY

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Abstract

Research activities in advanced propulsion concepts at the Jet Propulsion Laboratory are reviewed The concepts, which include high power plasma thrusters such as lithium-fueled Lorentz-Force-Accelerators, MEMS-scale propulsion systems, in-situ propellant utilization techniques, fusion propulsion systems and methods of using antimatter, were selected for study because each offers the potential for either significantly enhancing space transportation capability or enabling bold, ambitious new missions. This has been shown through systems and missions evaluation - a very valuable tool for determining the benefits and performance drivers of a concept. Potential performance of a new concept traditionally has been compared with that of chemical propulsion. However, because of the growing acceptance of electric propulsion in both government and commercial sectors, concepts must now show a benefit relative to Uris technology as well.

There is a range of maturity levels represented by the advanced concepts studied under this program, yet eaeh concept faces feasibility issues. Our research is focused on addressing, one-by-one, these feasibility issues. In addition to potentially addressing the propulsion needs of ambitious missions like those of the Human Exploration and Development of Space (HEDS) initiative, this research is aiding in fundamental scientific discoveries and developments in other technologies.

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I. Introduction

I.1 B a c k -

When using the words 'advanced propulsion', it quickly becomes evident that the definition of 'advanced' is context dependent In one context, the linear aerospike engines - chemical thrusters relying on O_2/H_2 propellant, designed by Rocketdyne, and planned for use on the Lockheed Martin X-33 reusable launch vehicle demonstrator and Venture Star - constitute advanced propulsion. For mission planners in the robotic spacecraft community, ion engines for solar-electric propulsion represent advanced technology because these thrusters signify a substantial departure from traditional chemical propulsion systems. However, after 37 years of development, the fundamental engineering and physics of ion thrusters are well understood. Electric propulsion systems are now the baseline technology for the New Millennium Deep Space 1 and Deep Space 4 missions. Within the Advanced Propulsion Concepts activity at JPL, and for the purpose of definition within this paper, 'advanced' means that the fundamental feasibility of a concept is in question. Our role at JPL is to identify and study the feasibility of new, far-reaching propulsion concepts that could, if viable, result in dramatic improvements in space transportation capability.

The mission statement of the Advanced Propulsion Concepts activity is to:

- Identify advanced propulsion concepts which offer theoretical performance significantly superior to that of state-of-the-art propulsion systems,
- Evaluate the feasibility of these concepts through experiment and analysis, and
- Provide guidance for NASA's investment strategy in advanced propulsion.

Because the time to implementation of most advanced propulsion concepts is beyond that which could be considered for near term mission planning efforts., support for this research has been provided separately by

NASA since 1981, independent of specific flight projects. More recently, this activity has become part of the Propulsion Research program being executed by the Marshall Space Flight Center.

I.2 The Need for Advanced Propulsion Concepts

It is a fascinating exercise to poll various people within NASA about what missions NASA would like to do that could be enabled by advanced propulsion concepts. A majority of the missions listed in response can be accomplished with the use of concepts that are at a rather high technology readiness level. See, for example, the JPL Propulsion Trades Study[1] which considers the use of advanced chemical propulsion, ion thrusters, and solar sails.

It is very reasonable that technology availability should govern mission objectives, However, it is the desire to accomplish extremely bold, ambitious goals, such as interstellar precursor missions or very fast piloted missions, that drives research in far term advanced propulsion,

Furthermore, there is a significant need for advanced space propulsion technologies with the potential for dramatic reductions in the cost of access to space. As shown in Figure 1, current Earth-to-orbit (LEO) launch costs are extremely high ($10,000/kg). A factor of 25 reduction to $400/kg will be needed to produce the dramatic increases in space activities in both the civilian and government sectors identified in the Commercial Space Transportation Study (CSTS)[2].

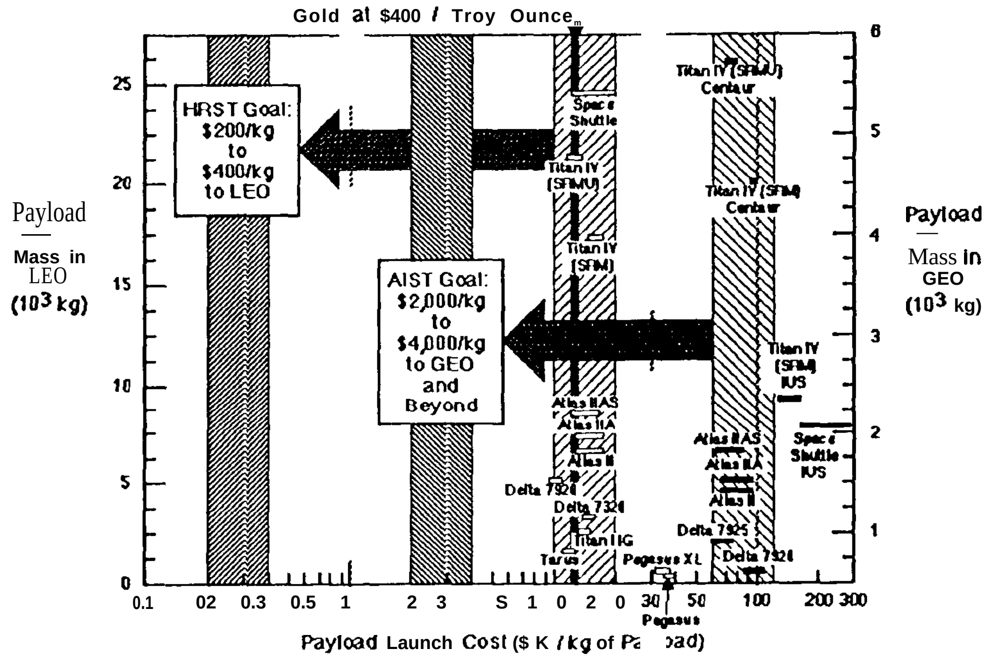

Figure 1. Launch Costs to LEO and GEO versus Payload Mass

I. 3 Approach

The approach we take in this activity is governed by four steps:

1, Identify advanced concepts,

2, Determine which concepts merit further study,

3. Address the feasibility issues of selected concepts, and

4. Periodically review progress and assess the need for continued effort,

We seek to identify new advanced propulsion concepts through a combination of annual workshops, SBIR and University proposals, and attention to emerging science and technology. Changing mission objectives and new technology developments can also lead us to revisit previously evaluated concepts.

The annual workshops also provide an important opportunity for cross-fertilization of ideas, techniques, and results for a wide variety of workers in the field of advanced space propulsion technology. The 1997 annual workshop hosted 75 attendees with 38 presentations from NASA, DoD, DoE, industry, and academia[3]. Specialist working groups have also been used to address speci fic t epics ranging from advanced electric propulsion to potential breakthrough-physics concepts'.

Some examples of recent scientific developments with potential benefits for propulsion include the experimental verification of metallic hydrogen through shock compression of the liquid phase[5]. Metastable solid metallic hydrogen, if it could be quenched from high pressures to ambient, would release a very large amount of energy by reversion to the diatomic insulating fluid. Such a fuel has a predicted specific impulse of approximately 2000s,

Other examples are the recent discoveries of the possibility of lunar ice[6] and the steady stream of water-bearing objects comparable to small comets disintegrating in Earth's upper atmosphere'. Both discoveries hold implications for in-situ propellant utilization concepts (see, for example, reference [8]).

Once identified, an advanced concept must be able to show promise for significant performance enhancements over existing or nearer term technologies, or be enabling of a previously intractable mission to warrant the investment required for its research, development, and implementation, Because of the growing acceptance of electric propulsion systems, the mission evaluation and systems analysis we perform to assess the merits of a new concept will now be referenced to ion thruster technology as well as chemical systems as the baseline capability.

1[is difficult to estimate how far in the future it will be before a technology reaches maturity when breakthroughs can result at any time or not at all. Some concepts can be investigated in the near term with a successful outcome leading to an immediate transfer to a technology development phase. Such concept implementation is limited only by the investment NASA chooses to make, which will be governed by the perceived need for the performance niche the technology will fill.

Although they all have feasibility issues requiring resolution, a diversity of concept maturity levels and applications are represented in our research, Pursuing advanced concepts which range in time-to-development helps to ensure constant, incremental improvements or enhancements to existing propulsion capability. Feasibility issues of advanced concepts are addressed one-by-one through a combination of in-house research, University contracts, and industry partnerships. This approach allows NASA to draw on the best expertise in specific technologies worldwide.

II. The Current Research Program

II.1 In-Situ Propellant Utilization

Reducing the initial mass in low-Earth-Orbit (IMLEO) of a spacecraft can enable a variety of robotic and piloted missions by dramatically reducing launch costs. One way to lower the IMLEO is to obtain some of the propellant required for the mission from extraterrestrial resources. Figure 2 shows a variety of propellant resources throughout the solar system. Among these, oxygen may be one of the most available.

The principle barrier to the use of oxygen as propellant in plasma thrusters is the development of a cathode which can tolerate the oxygen environment. Field emitter cathodes are efficient, low-power, and easily scaleable and have the potential to be functional in an oxygen environment. The successful demonstration of a cathode that operates on oxygen would enable In Situ propellant Utilization (ISPU) for a variety of advanced propulsion concepts. Applications include a trans-lunar cargo propulsion system,

In a collaborative effort with the University of Michigan, BMDO, arrd the Linfield Research Institute, hafnium carbide field-emitter arrays are being evaluated for operation in oxygen. These field emitter arrays have demonstrated low turn-on voltages, high current densities, and stable operation in a puked mode. The packing densities are on the order of 10^8 tips/cm^2, while the electric fields sustained are approximately 10^9 V/m. Single carbide tips have been shown to produce emission as high as 48 mA for transition metal carbides in a pulsed mode. Stable DC emission of 0.5 mA with lifetimes greater than 2400 hours have also been demonstrate

Tests of HfC emitters in mTorr pressure environments have yielded promising results. Future plans are to conduct a feasibility evaluation in the appropriate oxygen pressure regimes, This requires an emitter/gate electrode configuration that will prevent arcing. Other plans arc to study the effects, both structural and chemical, of ion bombardment to the tips.

Another project related to in-situ propellant utilization is a Phase 11 SBIR with the Wickman Spacecraft and Propulsion Company for investigating use of the Martian atmosphere as an oxidizer with a novel fuel[9].

The combustion can be used to drive turbo shaft engines for power generation and Martian land vehicle locomotion as well. In phase 1, a method of mixing the fuel with carbon dioxide for steady, controlled combustion was demonstrated, showing the feasibility of a microrover with a range of 170 kM.

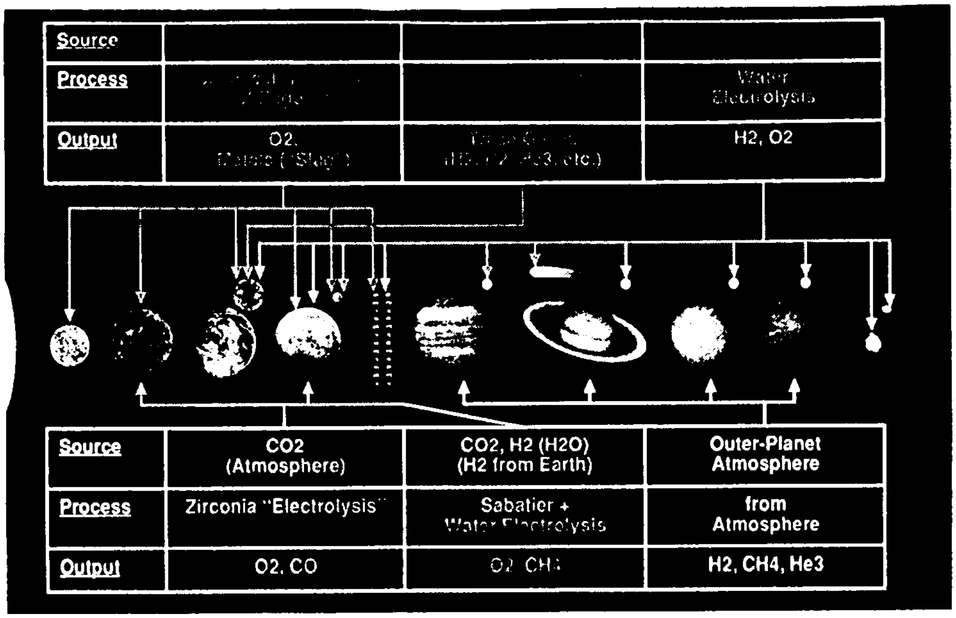

Figure 2. Resources for in-situ propellant utilization throughout the solar system.

<u>11.2 High Power Lorentz-Force Accelerator</u>

This activity is a collaboration between JPL, Princeton University, and the Moscow Aviation Institute (MAI). The purpose is to investigate the feasibility of megawatt-class, Lorentz-Force Accelerator (LFA) thrusters utilizing metal propellants such as Lithium or Lithium/Barium. Among all candidate plasma propulsion options, the lithium-fed LFA has the unique capability of offering high thrust densities (10^2 to 10^5 N/m*) and processing very high power (10^5 to 10^7 W) through a compact, simple device at a high specific impulse (4003-6000 s). These characteristics put the LFA thruster in a class by itself for application to many thrust-intensive and energetic missions[10,11] such as those being examined for the Human Development and Exploration of Space initiative. Furthermore, they may be well suited for fast robotic missions to the outer solar system,

Mission analyses performed at JPL to examine options for Mars cargo missions[12] show that MWe-class Li-LFA systems can perform Mars cargo missions with trip times of two years with vehicle masses that are approximately 80% of that of ballistic chemical or nuclear thermal propulsion options (Figure 3). LFA thruster Isp of 4,000 to 5,000 lbf-s/lbm and efficiency of 60% will be needed. This analysis was based on a SP- 100 nuclear electric propulsion scenario. However, solar electric options, like the Solar Clipper concept[13] would be applicable as well.

There has been considerable success with LFA devices in Russia in the 1970's; the steady-state operation of an engine approximately the same size as the 2.3 kWe NSTAR ion thruster was demonstrated for 500 hours at 500 kWe. A radiation-cooled thruster was also operated for 10's of minutes at over 1 M We. Good results with applied-field LFA thrusters were also achieved at Los Alamos National Laboratory during the late 1960's and early 1970's.

There are multiple feasibility issues facing LFA thrusters that must be addressed prior to technology development. These include spacecraft contamination by the condensable lithium propellant, anode thermal management, and cathode lifetime. It is also not clear whether the required performance can be attained at the power levels necessary for various ambitious deep space missions, or what the dominant failure modes will be.

Current LFA thruster research at JPL is centered on evaluating the feasibility of obtaining sufficient component lifetime. This work includes theoretical and experimental investigation of cathode erosion processes. Part of the cathode research effort has been supported at Thermacore Incorporated through an SBIR, and at Princeton University under a subcontract to Thermacore. Under the subcontract, a lithium-fed LFA with multi-channel cathode was designed and built along with its support subsystems. Currently, the system is the only known operational multi-channel cathode lithium LFA outside the Former Soviet Union. Earlier this year, a Li-LFA system was tested at 122 kWe, demonstrating 44% efficiency at 3500 s (see Figure 4). The wear rate on this cathode was consistent with a component lifetime of up to 1000 hours. The thruster is now being modified for 200 kWe operation and will be evaluated either in Russia or at JPL where we are developing the capability to perform such tests. This capability will enable long duration testing of lithium LFA devices at high power level - a combination of operating conditions currently unavailable anywhere in the world.

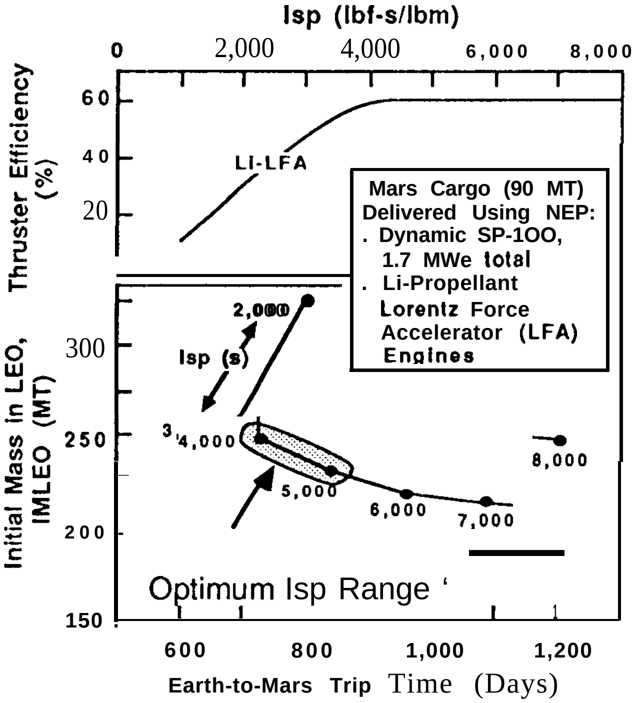

Figure 3. Impact of Li-Propellant LFA Engine Efficiency on Mission IMLEO and Trip Time*[2]

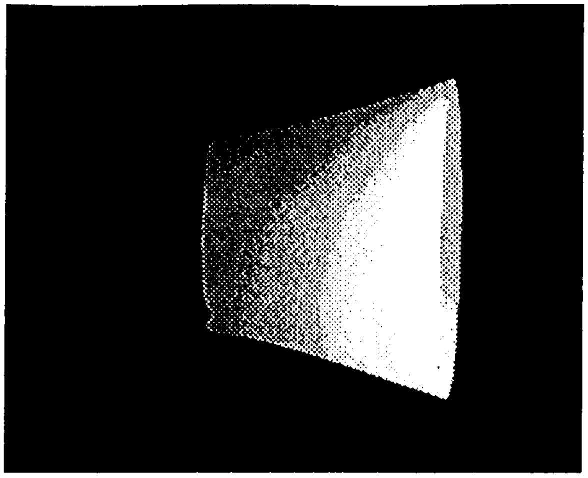
Figure 4. Li-LFA operating at 122 kWe at the Moscow Aviation Institute

II.3 Micropropulsion

The recent interest in developing microspacecraft in the 1-20 kg class necessitates the development of advanced, lightweight, small volume propulsion systems. For primary propulsion of interplanetary spacecraft, these micro-propulsion systems will have to provide large specific impulses to reduce propellant mass. Recent investigations performed within NASA's Pluto Fast-Flyby mission study indicated that for a 100 kg class spacecraft, thrust requirements for attitude control are on the order of 4 mN per thruster with impulse bits of less than 10^{-4} N·s. Assuming that similar pointing requirements will have to be maintained for micro-spacecraft, impulse bit requirements may have to be lowered by an additional one to two orders of magnitude for attitude control of microspacecraft in the 1-20 kg class. presently, such propulsion systems do not exist for either large delta-V or attitude control capability [14].

Using microfabrication techniques, we are investigating the feasibility of achieving order-of-magnitude mass and volume reductions over state-of-the-art propulsion systems while taking into account special MEMS design requirements (i.e. temperature, pressure, and material constraints).

One of the current research efforts is in micro-ion thrusters for large delta-v maneuvers of planetary microspacecraft. Design possibilities include both an RF ion engine concept to avoid micro-cathode erosion problems, and cold cathode technologies. The performance goals arc for a device capable of delivering 3000s Isp at μN thrust levels and at a power below 10 W. Breakdown tests of MEMS grids for this device are in progress - sec Figure 5. Under this program, computer simulations are being performed at the Massachusetts Institute of Technology for characterizing plasma production (e.g. ion production cost, power and pressure). This year there are plans to finalize the grid breakdown tests and fabricate devices for testing at Princeton University.

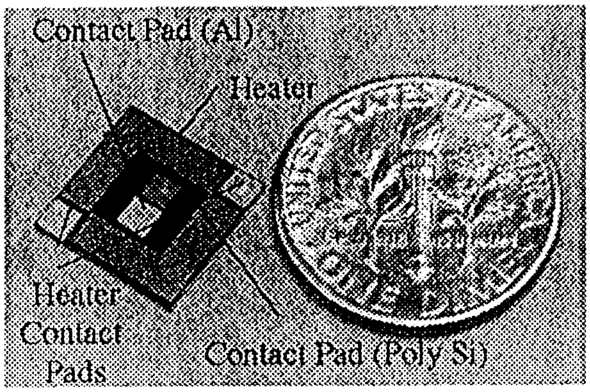

Figure 5. Grid Breakdown Test Chip

Other related project are two SBIR contracts with Marotta Scientific Controls, Incorporated. Both projects have been shown feasible at the Phase I level and have moved on to Phase 11 awards. The first of these is a micro-thruster concept employing MEMS and macro construction for a 0.0045 mN thrust, 1.3 x 10^{-5} N·s minimum impulse bit device, The second project is a micro-mass flow controller for a 3:1 Xe flow turn-down ratio. This device has applications in microspacecraft and conventional sized electric propulsion systems al ikc. Patents are pending for both concepts.

In April of 1997, JPL and the Air Force Phillips Laboratory jointly hosted a micropropulsion workshop. There were 70 participants from government, academia, and private industry. The goals of the workshop were to identify the most promising technologies, identify key feasibility issues, and develop a technology roadmap for micropropulsion.

It is important to note that MEMS-scale propulsion systems and components may have applications for systems other than microspacecraft; there may be benefits of redundancy, reliability, and scalability by using arrays of micromachined components.

II.4 Antimatter

Matter-antimatter annihilation offers the highest energy density of any known reaction substances. The energy density of 1.8 x 10^{16} J/kg for antiproton-proton annihilation is Orders of magnitude greater than chemical (1 x 10^{7} J/kg), fission (8 x 10^{13} J/kg), or even fusion (3 x 10^{14} J/kg) reactions, making the use of antimatter very attractive for propulsively ambitious space missions.

There are several different propulsion concepts which rely on matter-antimatter annihilation to provide propulsive energy. Most of these concepts use the annihilation reaction energy to heat propellant either directly or through a heat exchanger. Such concepts rely on a quantity of antimatter (10^{21} to 10^{28} antiprotons depending upon the application) not presently available; antiproton production capability at FermiLab is currently about 0.85 ng (10^{14} antiprotons) per year. Because the present antiproton production capability at both CERN in Switzerland and FermiLab in the U.S. is so drastically below that required for many advanced concepts, methods of using small amounts of antimatter to initiate fission and fusion reactions are currentfy being studied. Two such concepts have been proposed by Dr. Gerald Smith of the Pennsylvania State University. The first of these concepts is the Ion Compressed Antimatter Nuclear, or ICAN[15] method. ICAN is an inertial confinement fusion concept, requiring high intensity laser or ion beams to compress a target composed of Uranium, Tritium, and Deuterium, which is then bombarded by antiprotons. The antiprotons annihilate with nucleons in the fissionable target atoms, releasing on average 16 neutrons per annihilation event. The energy released in the fission reactions may be sufficient to initiate a fusion bum. The present conception of how to couple the energy released in the antiproton initiated fission/fusion reaction is by a technique somewhat analogous to the ORION concept[16]. Specifically, ICAN would operate by a series of explosions which heat and ablate a pusher-plate; the resulting expanding plasma would generate thrust[17]. Systems and mission studies of an ICAN propulsion system indicate the potential for fast piloted Mars missions (120 day round-trip, inclusive of a 30 stay), a 3-year fast Pluto flyby, and a 1.5 year piloted Jupiter mission.

More recently, the concept of Antiproton Initiated Microfusion (AIM) in electromagnetic traps was introduced[18]. It is expected that AIM could function with a variety of advanced fusion fuel targets such as p-B^{11}, seeded with approximately 2% U^{238}. There are two very significant benefits of AIM should it prove feasible. First, it would not require fuel pellet compression, which would enormously reduce the mass and complexity of a propulsion system based on this technology. The second benefit presents tantalizing possibilities; the daughter products resulting from antiproton induced fission of U^{238} have very little residual radioactivity as compared with those which result from conventional thermal neutron-induced fission of U^{235}[19]. Qualitatively, this results from the fact that the antiproton deposits enough energy in the nucleus to cause ejection of a large number of high energy (-40 MeV) neutrons. The nuclei of the resulting daughter products are much more stable. This may have significant consequences for the feasibility of developing clean nuclear propulsion systems. This concept requires an approximately equal number of antiprotons and fissionable atoms, such that fast neutrons ejected from initial annihilation events do not result in subsequent fission reactions by neutron capture in remaining U^{238} atoms. Reactions in the fissile material will significantly enhance the energy deposited in the fusion fuel target, An experiment to investigate the AIM concept was recently submitted by Penn State to the U.S. Department of Energy, Office of Energy Research[18].

Over the past several years, JPL's Advanced Propulsion Concepts program has supported researchers at Penn State to experimentally investigate antimatter trapping, storage, and manipulation for applications to space propulsion. Part of this work has been the development of the world's first portable Penning trap for the storage and transport of antiprotons (se-e Figures 6a,b). Last year saw the completion and initial testing of the Penning trap with electrons. Earlier this year, the storage of 107 H^- ions for 2 hours was demonstrated, This is a very significant result, as negative hydrogen ions have the same charge and virtually the same mass as antiprotons. Planned improvements in the vacuum systcm will permit storage for several days. Also, protons were successfully extracted from the trap and directed to a microchannel plate where they were detected Most recently, the Penn State team was successful in the capture and storage of 10 million antiprotons in ten successive pulses from the Low Energy Antiproton Ring (LEAR) at CERN. A surprising result of these experiments was that no annihilation above cosmic ray background levels was observed once the particles had been cooled below 1 eV. This is in contradiction with the expectation that the annihilation cross section would have a dependence inversely related to the particle velocities. The result was that the antiprotons were stored for a longer period than would have been predicted given the pressure in the system was approximately 10^{-11} Torr[21]. The implications of this result are extremely promising for the prospects for long term storage of antimatter that will be required for future experiments and space applications.

This year, the Penning trap will be filled at CERN with approximately 109 antiprotons. In addition, the first attempted antiproton catalyzed fission/fusion demonstrations for 1998 and 1999 are being readied. Support for these experiments now comes entirely from NASA. Initial target pellet compression tests at the Air Force SHIVA-Star facility were conducted last year with funding from the Air Force Office of Scientific Research.

The expedience being gained from storing and manipulating antimatter is seeding the ability to conduct experiments that can shed light on some fundamental questions in physics. Availability of the portable Penning trap has prompted the submission of a research proposal for performing precision tests of Einstein's Weak Equivalence Principle for antimatter[21]. Various hypotheses suggest the possibility of a violation of the Weak Equivalence Principle by antimatter by up to 200%. The proposed experiment would be carried out on the International Space Station, enclosed in the JPL Low Temperature Microgravity Physics Facility (LTMPF). The experimental objective will be to measure the position of an antiproton moving in a magnetron orbit in a "weighing" trap. Accurate measurements of particle position as a function of time wilt lead to the determination of antiproton weight.

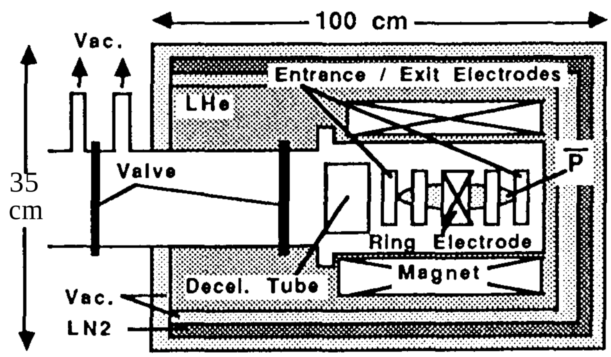

Figure 6a. Diagram of PSU Portable Penning Trap for Antiprotons.

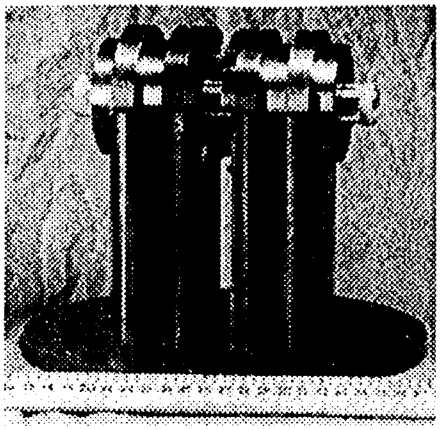

Figure 6b. PSU Portable Penning Trap for Antiprotons and support structure.

11.5 Fusion

While the ICAN concept relies on the novel use of antiprotons, it is, fundamentally, a fusion propulsion concept. Numerous other fusion energy-based propulsion concepts have been proposed, and many are currently under investigation elsewhere[22]. Almost invariably, these concepts can be categorized as inertial- or magnetic- confinement fusion based, and require massive system components One possible exception to this is the Dense Plasma Focus (DPF).

The DPF is a table-top device presently being examined under the advanced propulsion concepts activity, as well by other independent investigators[22]. Lawrenceville Plasma Physics, in cooperation with Centrus Plasma Technologies, is performing DPF simulations and experiments. The goal of this research is to assess the feasibility of a fusion propulsion system based on the use the pulsed magnetic pinch effect. A DPF propulsion system would operate at very high specific impulse, yet at a thrust-to-weight ratio that is orders-of-magnitude below those of other fusion systems. This device may be capable of operating on a number of fusion fuels including $p\text{-}B^{11}$. However, unlike most inertial- or magnetic-confinement fusion systems, it is not necessary that it operate at a high gain. In fact, the gain of the DPF thruster is estimated to be around one, corresponding to scientific break-even.

The DPF device consists of two oppositely charged concentric conducting cylinders. The outer and inner conductors are the cathode and anode, respectively. The device is tilled with deuterium gas, then a capacitor is discharged across the conductors, creating plasma. Current flowing in the plasma induces the pinch effect, and results in the formation of a sheath of plasma filaments. Through a process which is one of the subjects of study in this research, the filaments lead to the production of an unstable plasmoid - a very high density, high magnetic field region - in the device. Strong electric fields accelerate ions from the plasmoid in one direction, and electrons in the other. The electrons serve to further heat the high density plasma region, that may then undergo fusion reactions.

Tasks for this year are to benchmark the predictions of a fully 3D particle-in-cell (PIC) code against D-D fuel DPF experiments performed in 1994 at the University of Illinois. This will be followed by the execution of optimization simulations to determine electrode design and experimental conditions, as well as fabrication of electrodes and insulators, and modification of an existing DPF apparatus for high temperature operation.

In Figure 7, ion and DPF electric propulsion systems are compared for the case of an interstellar precursor mission traveling to 1000 A.U. in 50 years. The comparison indicates the gain of the DPF system required to show performance significantly better than the ion propulsion system, where the figure-of-merit here is vehicle wet mass.

Because of its small size and relatively simple design, the DPF device represents a departure from other fusion systems, as it permits fundamental fusion research at very low cost.

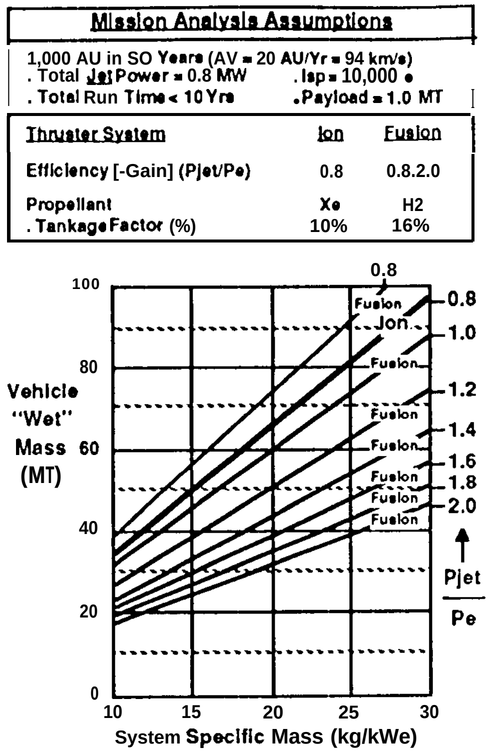

Figure 7. Comparison of Ion and DPF Thruster for a Thousand A.U. Mission.

II.6 Advanced PropuLsion Concepts Mission and Systems Evaluation

Most advanced propulsion concepts research activities have as their objectives to understand the underlying physics and to evaluate the feasibility of an advanced propulsion device. One cost effective-method for circumventing the difficulties encountered in laboratory testing of some advanced concepts is to conduct virtual experiments; we arc developing a first-principals-based, high-performance virtual simulation capability on massively parallel supercomputers for the evaluation of advanced propulsion concepts.

Advanced particle simulation algorithms on parallel supercomputers for study of ion thrusters, high-power microwave devices, and instabilities in space plasmas have already been developed. We are currently able to perform targc-scale particle simulations that track several hundreds of millions of particles.

WC plan to build numerical test beds using our parallel computing capabilities for many advanced propulsion systems including magnetic sails, electrodynamics tethers, microthrusters and high power plasma thrusters. These numerical test beds would enable virtual experiments to validate the life and performance of various propulsion devices. It would also allow for the study of interactions and impacts induced by these thrusters on other spacecraft components.

A recent example of the application of this capability is an analysis of the Magnetic Sail concept proposed by Zubrin[24]. The concept is for a magnetic field generated by a superconducting loop to deflect plasma wind, thereby creating thrust. Single particle models (in configurations of both axially and normally directed charged particles) were used to predict performance. For comparison with prior estimates, we modified a 3-D particle-in-cell (PIC) code to develop a 3-D single particle model. The thrust predicted by these simulations was an order-of-magnitude lower than that estimated previously

Mission evaluation performed from a complete systems perspective is another element of the numerical testbed that is crucial to the advanced propulsion concepts program; it provides quantification of potential mission benefits of an advanced concept. Because the various performance characteristics of a technology (e.g. specific impulse, efficiency, and specific mass) can be treated parametrically in an analysis, this capability is used to identify the system parameters that arc the primary performance drivers for a mission and conversely, to identify those that have little impact on performance. This technique aids in rapid identification of concepts that yield no significant performance enhancements so that they need not be pursued further.

The results of one recent mission evaluation arc illustrated in Figure 8. Here, we examined the performance an inflatable solar sail would have for a robotic microspacecraft Mars orbiter. It was found that a 100-m diameter inflatable solar sail could deliver a net payload of 48 kg to Mars in 725 days using a Pegasus XL / Star 27 launch vehicle[25]. Several different sail areal densities are shown on the chart, all of which are currently below the 20 g/m2 being considered for near-tcrm demonstration missions[26].

Applications of solar sails have generated a great deal of interest in recent months as evidenced by the JPL Solar Sail Workshop held in February 1997 and numerous mission studies. These studies include a January-May 1997 study (funded by SEC) of a Solar Polar Sail Mission requiring a 160m x 160m sail, a Comet Nucleus Sample Return mission, and an NOAA Geomagnetic Storm Warning mission using a 67m x 67m inflatable solar sail. The propulsive requirements for this last mission arc ideally suited for near-term solar sails; the Geostorm spacecraft requires a non-Keplerian orbit (sub-L1 Positioning") and a sail density of a very achievable 30 g/m2. A summary of some other potential sail missions is shown in Table 1. The most recent solar sail mission study performed at JPL has been for a low cost solar sail demonstration. The scenario for the demonstration mission is for spacecraft injection into a 620 x 35,900 km GTO, deployment of the solar sail and supporting structure, followed by perigee altitude increase above 2000 km in 23 days, Lunar distance reached in 400 days, and Earth escape by 600 days. This concept would require a 40m X 40m sail 7.5 mm thick (specific mass 20 g/m2). Total sail mass would be 41.7 kg for a 36.8 kg spacecraft. A successful solar sail demonstration would be an enormous step towards demonstrating the utility of this technology, and help to motivate improvements in thin manufacturing, handling, bonding, and storage that could enable some of the more ambitious missions. Specifically, development of 6 g/m2 sail films may enable a Pluto mission with a 6 year trip time, or a 100 AU mission in 16 years[27].

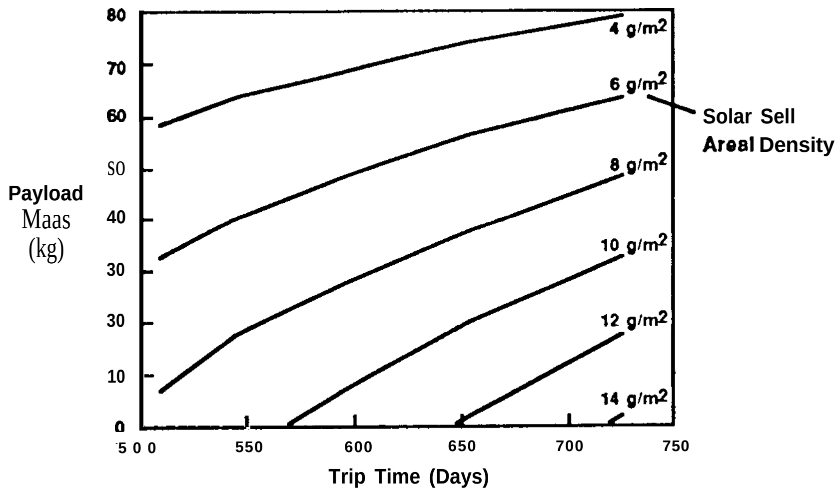

Figure 8. Net Payload Mass versus Earth-to-Mars Trip Time
(Earth-to-Mars Trip Time Includes Heliocentric Transfer and Mars-Orbit Capture)

Mission	Launch Vehicle	Sail Density g/m2	Deploy Hrdwre kg	Sail Mass kg	S/C Mass kg	Total Mass kg	Sait Size m	Trip Time yrs
solar Probe	Taurus/326	6	20	100	30	150	130X 130	3.4
solar Probe	Taurus/326	6	20	200	80	300	183x183	3.4
Sun-sync Hg Orb	Taurus+Star37	6	20	42	180	242	86x 86	3.5
Mercury Orbiter	Med-Lite	6	20	240	180	440	200 x 200	1.0
Inflatable Mars	PegaausXL+S27	8	20	62	28	110	88x 88	2.0
n flatable Msrs	PegasusXL+S27	12	20	93	17	110	88x 88	2.0
'upiter Polar Orbiter	Unknown	6	20	353			242 X 242	3.7
'luto Express	Taurus+ Star37	5.5	20	210	100	330	195X 195	10.1
kth/Vests Rendez	Taurus+ Star37	6	20	103	77	200	130x 130	3.8
MBAR/Return To:								
Vesta--Taurua+Star37		6	20	124	81	225	144 x 144	5.3
Vests--Taums+Star37		5	20	242	128	390	220 x 220	

Table 1. Summary 01 solar sail missions.

IV. Summary

For a very modest investment by NASA, the research conducted under this program ean have an enormous impact on a variety of NASA programs, basic scientific research, and spin-off technologies. For instance, megawatt-class plasma thrusters, specifically Li-LFA engines, may provide a solution for the propulsion problem of the multi-billion-dollar NASA/HEDS initiative. Similarly, the antimatter/fusion work may have unmatched future potential for the exploration and use of space as well as result in numerous medical and terrestrial power applications.

Any organization whose product is technology-based, whether government or industry funded, is well advised to consistently invest in future products or capabilities. Doing so expands our vision of what we can accomplish, Investment that is long-term and sustained is required for any of the advanced concepts we pursue to reach fruition.

IV. Acknowledgments

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